HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

THESIS OF THE DOCTORAL (PHD) DISSERTATION

CHEMICAL CLASSIFICATION OF TANZANIAN SODA-SALINE WATERS (EASTERN RIFT VALLEY)

BY

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1. INTRODUCTION

1.1. Background

Inland alkaline soda waters (IASW) are characterized by a permanent pH exciding 9 (pH>9), enriched with dissolved Na^+, HCO_3^- + CO_3^{2-}, and sometimes higher dissolved Cl^-, and SO_4^{2-} and lower amounts of alkaline earth metals ions (Ca^{2+} and Mg^{2+}) (Boros & Kolpakova, 2018; Deocampo & Renaut, 2016; Eugster & Jones, 1979; Jones & Deocampo, 2003). In contrast to other saline lakes, IASW is distinguished by their higher alkalinity with very dilute inflow originating from the surrounding volcanic terrain (Deocampo & Renaut, 2016; Pecoraino et al., 2015). IASW is commonly found in arid and semi-arid regions globally, including the East African Rift Valley (EARV), the Great Basin in the United States, Central Europe, China, and Russia (Boros & Kolpakova, 2018; Deocampo & Renaut, 2016; Kempe & Kazmierczak, 2002; Sorokin et al., 2014). IASW develop in hydrologically closed basins (without the outlet) and evaporation surpasses the drainage water inputs from the surrounding escarpments (Deocampo & Renaut, 2016; Eugster & Jones, 1979; Eugster, 1980; Pecoraino et al., 2015). The lake basin's surrounding geology is rich in Na^+ and low in Mg^{2+}/Ca^{2+} silicates (Grant & Yu, 2011). Leaching of volcanic minerals from nearby rocks and soils increases the lake's alkalinity. Key environmental factors such as geological, hydrological, and climatic conditions are major contributors to the unique chemical compositions of IASW (Deocampo & Renaut, 2016; Eugster, 1980; Pecoraino et al., 2015).

IASW are biodiversity hotspots and highly productive, despite the harsh environmental conditions (Inelova et al., 2024; Li et al., 2024). Soda lakes are the habitats of diverse microbial communities, such as phytoplankton, algae, archaea, bacteria, and cyanobacteria, which thrive in environments with elevated alkalinity and salinity (Ali et al., 2022; Grant & Jones, 2016; Grant, 2004; Jeilu et al., 2022; Jones et al.,1998). Microbial communities are crucial in the biogeochemical cycling of carbon, nitrogen, and Sulphur (Sorokin et al., 2014, 2015). The unique chemistry and ecology of IASW attract scientists interested in extremophiles, biogeochemistry, and astrobiology. These ecosystems support research in biodiversity conservation, biotechnology, and industrial applications. IASWs are popular tourist destinations, especially for migrating water birds. IASW watersheds also provide vital ecosystem services, including water for households, livestock, and wildlife, salt extraction, climate regulation, water purification, nitrogen cycling, and recreational opportunities.

1.2. Problem Statement and Justification

Despite the ecological benefits of Tanzania's IASW, their chemical composition is threatened by human activities, climate change, and inadequate monitoring and waste management (Tebbs et al., 2013; Yona et al., 2022). While Lake Natron has been well-studied (Fritz et al., 1987; Mgimwa et al., 2021; Robinson, 2015; Tebbs et al., 2013; Yona et al., 2022; Zaitsev & Keller, 2006), recent data on the chemical compositions of other regional IASWs, such as Lakes Balangida, Balangida Lalu, Mikuyu, Singida, Kindai, and Sulunga, remain limited, with available data dating back to the 1970s (Hecky & Kilham, 1973). To gain a better understanding a comprehensive, up-to-date study is essential. Furthermore, the classification of the region's IASW into the respective water chemical types and their geographical distributions has not been done. In this study, we adopted Boros & Kolpakova, (2018) classification criteria to classify the IASW in eastern Tanzania into their distinctive water chemical type. The study aimed to (i) review the chemical properties of IASW in the Eastern African Rift Valley (EARV), (ii) assess the chemical composition of IASW in the Eastern Tanzania Rift Valley (ETRV), (iii) classify lakes into distinct water chemical types, (iv) assess the geographical distribution of these types, and (v) examine environmental and anthropogenic influences on IASW chemistry using remote sensing and GIS. The findings provide an overview of IASW chemical composition in East Africa, current chemical status, distinctive water types, and geographic distribution in the ETRV, setting a baseline for understudied lakes. This up-to-date information is crucial for scientists and government agencies in monitoring and managing these ecosystems.

1.3. Research Objectives and Questions

This study aims to review the chemical properties of IASW in the Eastern African Rift Valley (EARV), assess the chemical composition of IASW in the Eastern Tanzania Rift Valley (ETRV), classify lakes into distinct water chemical types, assess the geographical distribution of these types, and examine environmental and anthropogenic influences on IASW chemistry using remote sensing and GIS.

Objective 1: To review the chemical properties of IASW in the EARV

1.1. What is the status of the chemical properties of IASW in the EARV?

1.2. How are the IASW water classes of each country distributed in the EARV?

1.3. How do Na^{+}, Cl^{-}, CO_3^{2-}, and TDS spatially distributed in the EARV?

Objective 2: To classify the IASW in the ETRV into their distinctive water chemical types

2.1. How many lakes are classified as "soda", "soda-saline" or "saline" in the ETRV?

Objective 3: To assess the spatial distribution of the determined chemical types in ETRV

3.1. How are the IASW water chemical types spatially distributed in the ETRV?

Objective 4: To examine the key environmental elements influencing the chemistry of soda-saline lake waters using Remote sensing and a GIS-based approach

4.1. How do the key environmental drivers (Climate, soil types, geological features and anthropogenic activity), influence the water chemistry of IASW in the ETRV?

2. MATERIALS AND METHODS

2.1. Description of the study area

This dissertation examines the chemistry of inland soda-saline lake waters in the EARV system (Figure 1), with a focus on the ETRV (Figure 2). The East African Rift System (EARS) is divided into two sections: the eastern and western rifts. The eastern rift runs from northern Ethiopia through Kenya to central and southern Tanzania, meeting the western branch at the Mbeya region. The western rift stretches from Uganda, Rwanda, and Burundi, down through western to southern Tanzania, continuing through Malawi to Mozambique. The EARS features unique geological and hydrological phenomena, including active volcanism, tectonic movements, earthquakes, and geothermal activity (Dawson, 2008b; Scoon, 2020). EARS is characterized by high escarpments, volcanic peaks, and shallow basins, the EARS has diverse geology with sedimentary rocks, clay-rich soils, and volcanic rocks like basaltic lava (Owen et al., 2018; Scoon, 2018). Common minerals in the region include nephelinite with nepheline, augite, anorthoclase, and albite (Scoon, 2018). The natural vegetation is typical of a savannah ecosystem, dominated by grasslands with bushland in the hilly areas.

The region, particularly the ETRV, experiences intense precipitation from November to May, followed by a drought from July to October. It has an arid to semi-arid climate, with temperatures dropping to around 2°C in June or July and reaching highs of 35°C in February, September, and October (Catherine et al., 2015; Mwabumba et al., 2022). This climate promotes high evaporation rates, leading to greater water loss than precipitation (Olaka et al., 2010).

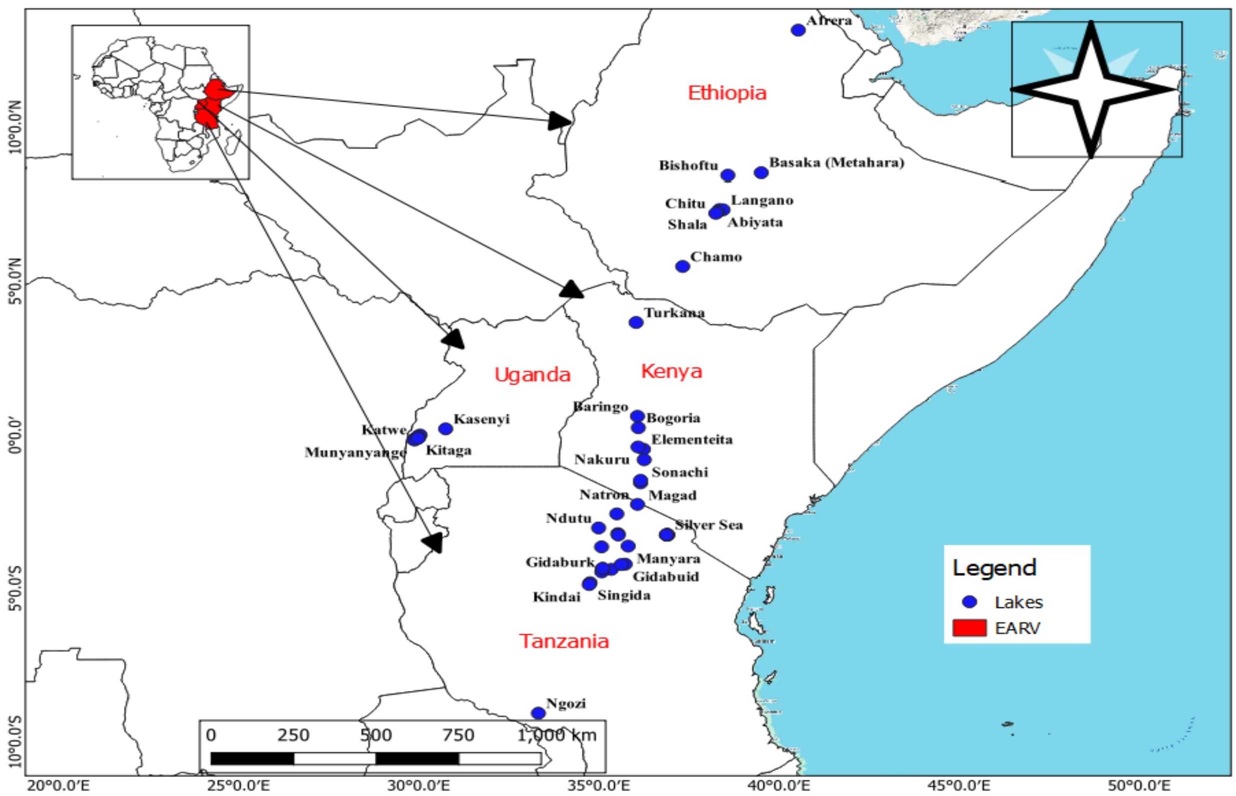


Figure 1: Locations and spatial distributions of the investigated inland saline waters in East Africa by countries

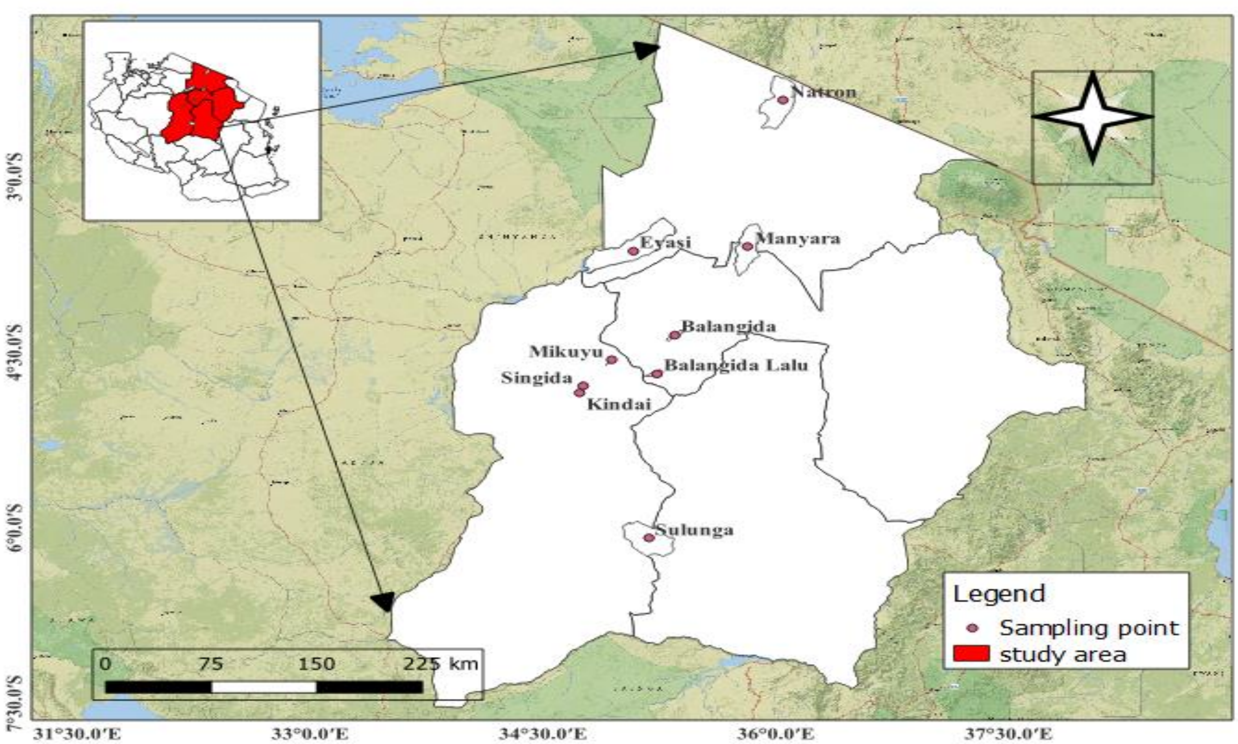


Figure 2: Locations of the investigated lakes along eastern Tanzania Rift Valley

2.2 Data acquisition and analysis

2.3 Chemical Properties of IASW in EARV

The chemistry and pH (when available) of the IASW in the EARV were reviewed based on published articles from 1965 to 2022. This study focused on lakes with a minimum total dissolved solids (TDS) concentration of 1 g/L. We researched relevant peer-reviewed articles using academic databases like Scopus, CAB Direct, and Web of Science, along with Google Scholar and specialized websites. Mean values were used where multiple datasets from different depths, times, or seasons were available. Data from publicly available studies may vary in accuracy and repeatability but were analyzed using a standard method.

2.4 Carbonate estimation and water chemical types classification

Most authors reported carbonates as total alkalinity using methyl orange and phenolphthalein indicators. This work estimated precise carbonate and bicarbonate levels from total alkalinity and pH following Boros's (2023) method. We used the criteria Boros & Kolpakova, (2018) proposed to classify the water chemical types in the EARV.

2.4 Spatial GIS and Statistical Analysis

This study employed the Global Moran's I statistic to quantify the degree of spatial autocorrelation HCO_3^- + CO_3^{2-}, Cl^-, $SO_4^{2-}$and TDS. A spatial weights matrix (contiguity-based, distance-based, or k-nearest neighbours) was constructed to define the spatial relationships between features. The Global Moran's I statistic was computed to evaluate the overall spatial autocorrelation of the attribute values. The z-score and p-value associated with Moran's I statistic were calculated to determine the statistical significance of the results.

2.5 Water sampling and sample analysis

From September 12 to September 18, 2022, we conducted a field expedition in the eastern Tanzania Rift Valley, as illustrated in Figure 2. We collected three composite samples from each lake except in Lake Balangida (which was nearly dry) where we collected one sample. In the field we measured After sample collection, we immediately measured pH, temperature, EC, TDS, and DO using an Oakton 600 Series Waterproof Portable Meter Kit. For cation analysis (Na^+, K^+, Ca^{2+} and Mg^{2+}) samples were filtered through a 0.45 µm filter and acidified with pure HNO_3 to a pH of 2. Conversely, samples for anion analysis (HCO_3^-, CO_3^{2-}, Cl^-, and SO_4^{2-}) were left unacidified. All samples were stored in an ice bath for transport to the laboratory for analysis. The cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were examined using ICP-MS; Cl^- by argentometric titration; CO_3^{2-} and HCO_3^- by alkalinity titration; and SO_4^{2-} by turbidimetric titration method.

2.6 Climate and Drought Analysis

We investigated climatic variability using satellite-derived precipitation and temperature data from selected locations along the watersheds of Lake Natron, Eyasi, and Manyara in northern Tanzania. This approach was chosen due to the limitations of historical data from meteorological stations, which are unevenly distributed in the region (Mwabumba et al., 2022). We obtained satellite-derived precipitation data from the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) datasets (Funk et al., 2015). We obtained satellite-derived temperature data from MERRA-2, a component of NASA's POWER project, which offers a spatial resolution of 0.5°(Westberg et al., 2013). The satellite-derived climatic data, were collected for the period from 1981 to 2022. We adopted the Standardised Precipitation Evapotranspiration Index (SPEI) invented by Vicente-Serrano et al., (2010), to assess the frequency and intensity of droughts in the region.

2.7 Land use land cover (LULC) changes classification

LULC changes in Northern Tanzania were analyzed using Landsat images from 2000, 2014, and 2023. These years were chosen to assess both short- and long-term changes, with images selected for minimal cloud cover (less than 5%). Landsat-5 TM and Landsat-8 OLI images from the Google Earth Engine (GEE) platform were processed on GEE to classify LULC types across the study area. The spectral bands (Blue, Red, Near Infrared, and Shortwave Infrared) were processed, and indices like the Normalized Difference Moisture Index (NDMI), Normalized Difference Built-up Index (NDBI), and Normalized Difference Vegetation Index (NDVI) were derived. These bands and indices were then used as input features for supervised classification, with a spatial resolution of 30 meters. We identified six LULC categories: water bodies, forests, shrubs/grasses, bare land, agricultural land, and built-up areas. For each image, at least 330 sample polygons were selected, and then randomly divided in half where 50% were used for training and the remaining 50% for validating the classification accuracy (Ahmed *et al* 2024). The Random Forest (RF) classifier was chosen to categorize the three Landsat images due to its proven high accuracy in identifying diverse land use and land cover (LULC) classes across various environments (Rodriguez-Galiano et al., 2012; Thonfeld et al., 2020)

3. RESULTS AND DISCUSSION

3.1 Chemical properties and chemical type classification of EARV

The chemical properties of the EARV are comprehensively detailed in Table 1 by Lameck et al., (2023). Table 1 presents the regional number of the classified lakes by country following Boros & Kolpakova,(2018) classification and Figure 3 provides a visual representation of the water chemical type of the IASW of the EARV. Results showed soda water lakes account for 73.2% (41) of the region's lakes, with the largest number in Tanzania (20 lakes, 46.7%), followed by Ethiopia (9 lakes, 22%), Kenya (8 lakes, 19.5%), and Uganda (4 lakes, 9.8%). Soda-saline types account for 12.5% (7) of the lakes in the region, with all of them located in Tanzania. Additionally, 14.3% (8) of the lakes are classified as saline water, primarily found in Uganda (4 lakes, 50%), Tanzania (3 lakes, 37.5%), and Ethiopia (1 lake, 12.5%). The study emphasizes the prevalence of soda water and soda-saline lakes in the region. This distribution highlights regional variations in lake chemistry, with Tanzania hosting the majority of soda water soda-saline lakes. Furthermore, the presence of saline water types, particularly in Uganda, Tanzania and Ethiopia adds another layer of complexity to the region's hydrochemistry.

3.2 Spatial distributions of Na^+, Cl^-, CO_3^{2-}, and TDS in EARV

The Moran's I spatial autocorrelation analysis reveals that the distribution of Na^+, Cl^-, SO_4^{2-}, $HCO_3^- + CO_3^{2-}$, and TDS across the EARV shows significant spatial autocorrelation ($p < 0.0001$), as presented in Table 2. Na^+, Cl^-, and SO_4^{2-} exhibit strong clustering patterns, whereas bicarbonate/carbonate shows weaker clustering. These clustering patterns indicate non-random spatial distributions for all ions and TDS across the EARV. This spatial pattern reflects regional influences such as geological sources (mineral dissolution), weathering or biological processes, hydrological connectivity, or evaporation rates, which contribute to varying these ions across the study area.

Figure 4 depicts the geographical distribution patterns Na^+, Cl^-, CO_3^{2-}, and TDS in EARV. The results revealed that the spatial distribution patterns of Na^+, Cl^-, CO_3^{2-}, and TDS in the Eastern Rift generally showed an increasing concentration gradient from north to south, except for Afrera Lake in northern Ethiopia and lakes in Uganda (Western Rift). The north-south concentration gradient of Na^+, Cl^-, CO_3^{2-}, and TDS in the Eastern Rift is influenced by the region's active volcanic and tectonic activity (with most lakes of volcanic and tectonic origin), arid to semi-arid climate, prevalence of volcanic rocks, recharge from alkaline hot springs, and deep groundwater connectivity beneath the Rift Valley (Eugster, 1970; Fazi et al., 2018; Schagerl & Renaut, 2016). High concentrations of major ions in EARV lakes may lead to the salinization of freshwater and soil (Kaushal et al., 2021). Key environmental factors driving this salinization include dissolved salt intrusions and climate change impacts (Godebo et al., 2021; Musie & Gonfa, 2023; Zebire et al., 2019). Rising temperatures in the region further exacerbate evaporation, causing concentrated salt deposits to accumulate in the soil. Over time, these factors could severely reduce soil fertility and limit the availability of clean freshwater for both human and wildlife populations in the Rift Valley.

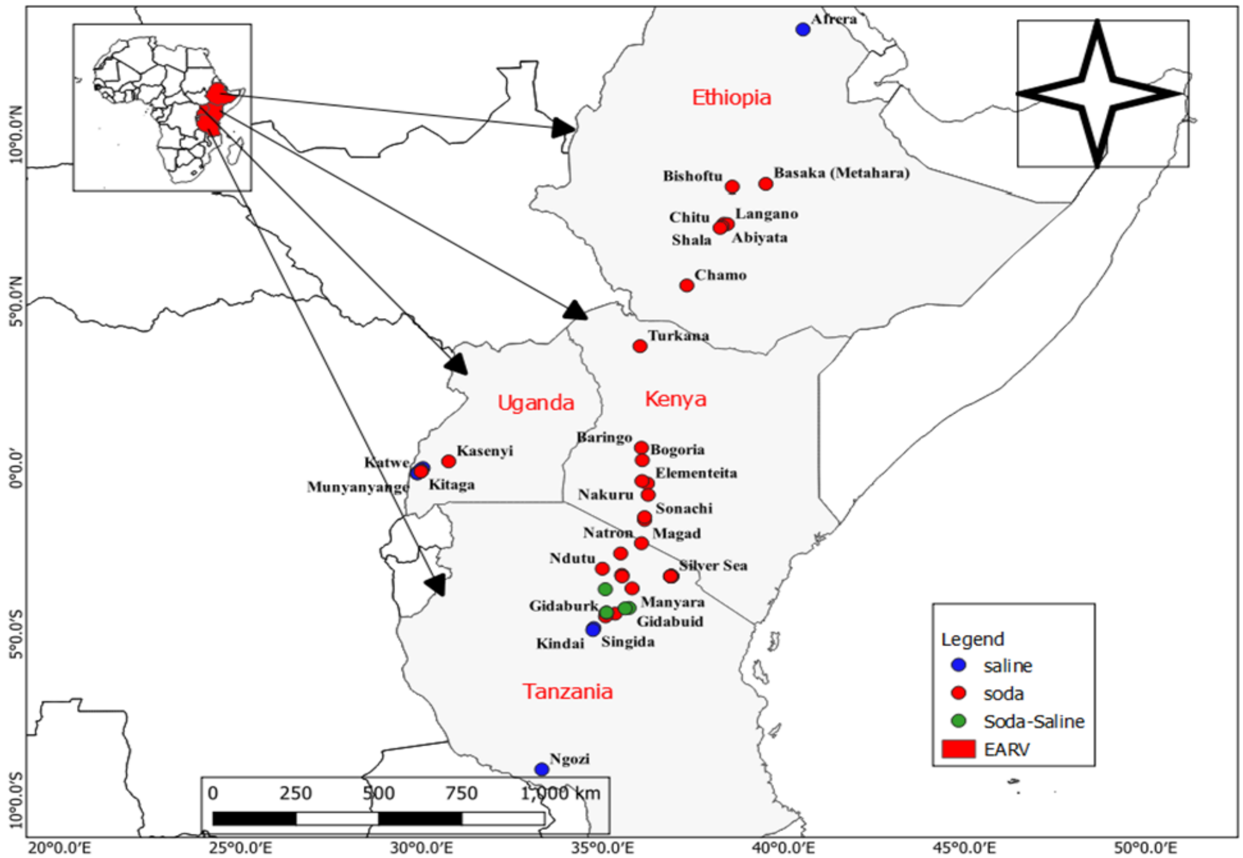


Figure 3: The water chemical type of the IASW of the EARV

Table 1: Regional number of the classified lakes by country

Country	Soda	Soda-saline	Saline	Total
Tanzania	20	7	3	30
Kenya	8	0	0	8
Ethiopia	9	0	1	10
Uganda	4	0	4	9
Total	41	7	8	54

Table 2: The statistical results of spatial autocorrelation with the inverse Euclidean distance method by using chemical variables

Autocorrelation	Na^+	Cl^-	SO_4^{2-}	$HCO_3^- + CO_3^{2-}$	TDS
Moran's Index:	0.392495	0.437955	0.470169	0.280613	0.389283
z-score:	4.714042	5.239139	5.701369	3.460942	4.675865
p-value:	p<0.0001****	p<0.0001****	p<0.0001****	0.000538***	p<0.0001****

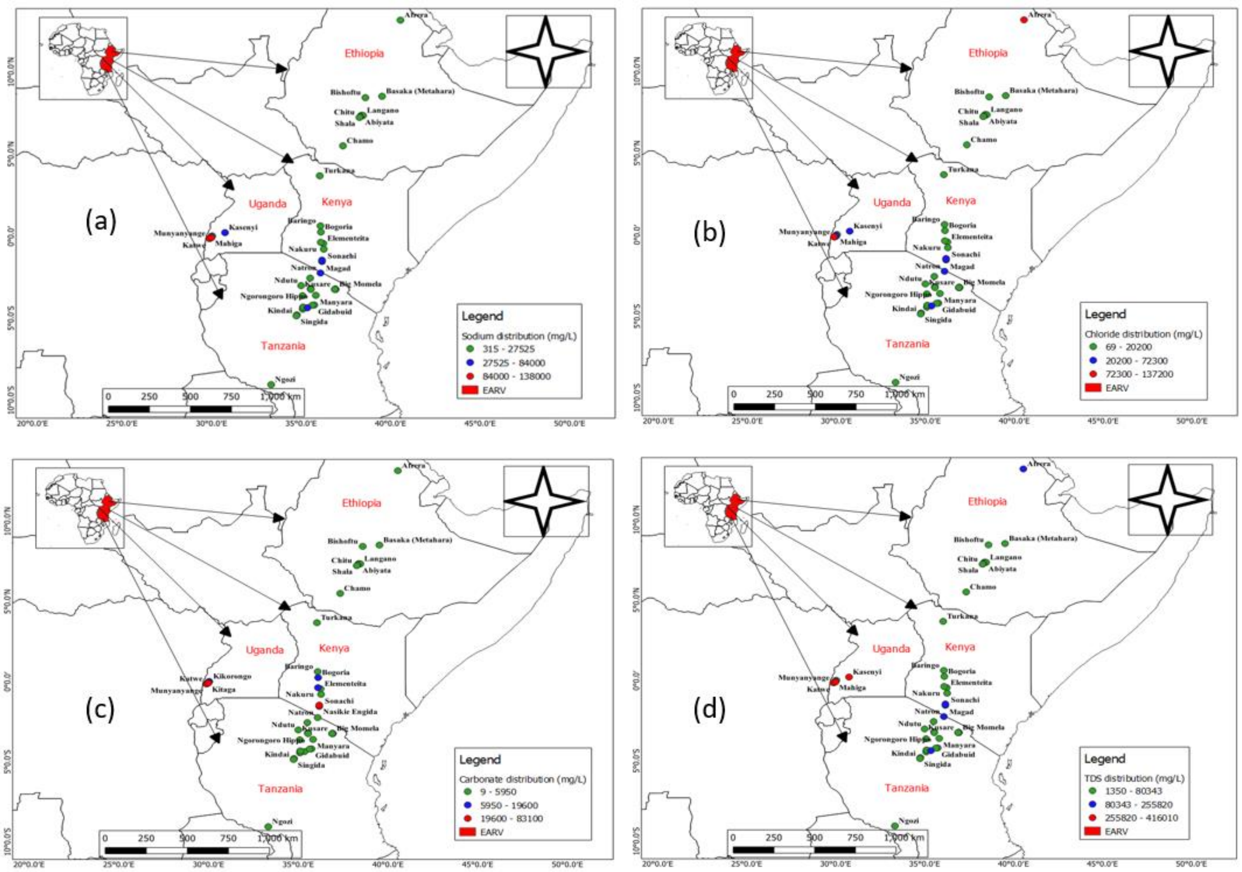


Figure 4: Spatial distributions of (a) Na^+ (b) Cl^- (c) CO_3^{2-}, and (d) TDS in EARV

3.2 Hydrochemical Characteristics of ETRV Lakes

The ETRV Lakes display distinct hydrochemical types, as shown in Figure *5*. Lakes Natron and Manyara exhibit Na-K-HCO_3 composition, which reflects a strong volcanic influence in northern Tanzania (Abdallah et al., 2023; Deocampo & Renaut, 2016; Deocampo, 2004; Foster et al., 1997; Pecoraino et al., 2015) as these lakes lie within active tectonic zones where volcanic processes enrich the water with alkali and carbonate ions. In contrast, lakes Balangida and Balangida Lalu exhibit a Na-SO_4 composition, possibly due to weathering of sulfur-bearing minerals and agricultural runoff. This points to the impact of human activities, such as fertilizer use on farms around the vicinity of the lake, which may result in increased sulfate levels. Such changes can alter aquatic habitats, potentially affecting species composition and leading to shifts in ecosystem dynamics. Meanwhile, Lakes Sulunga, Kindai, Singidani, Mikuyu, and Eyasi are characterized by a Na-Cl type, linked to evaporative concentration and halite mineral dissolution. The presence of salt-rich hydrochemistry in these lakes implies that arid to semi-arid climatic conditions and high evaporation rates drive mineral concentration. The variations in hydrochemical types underscore the sensitivity of these lake systems to both natural and anthropogenic influences.

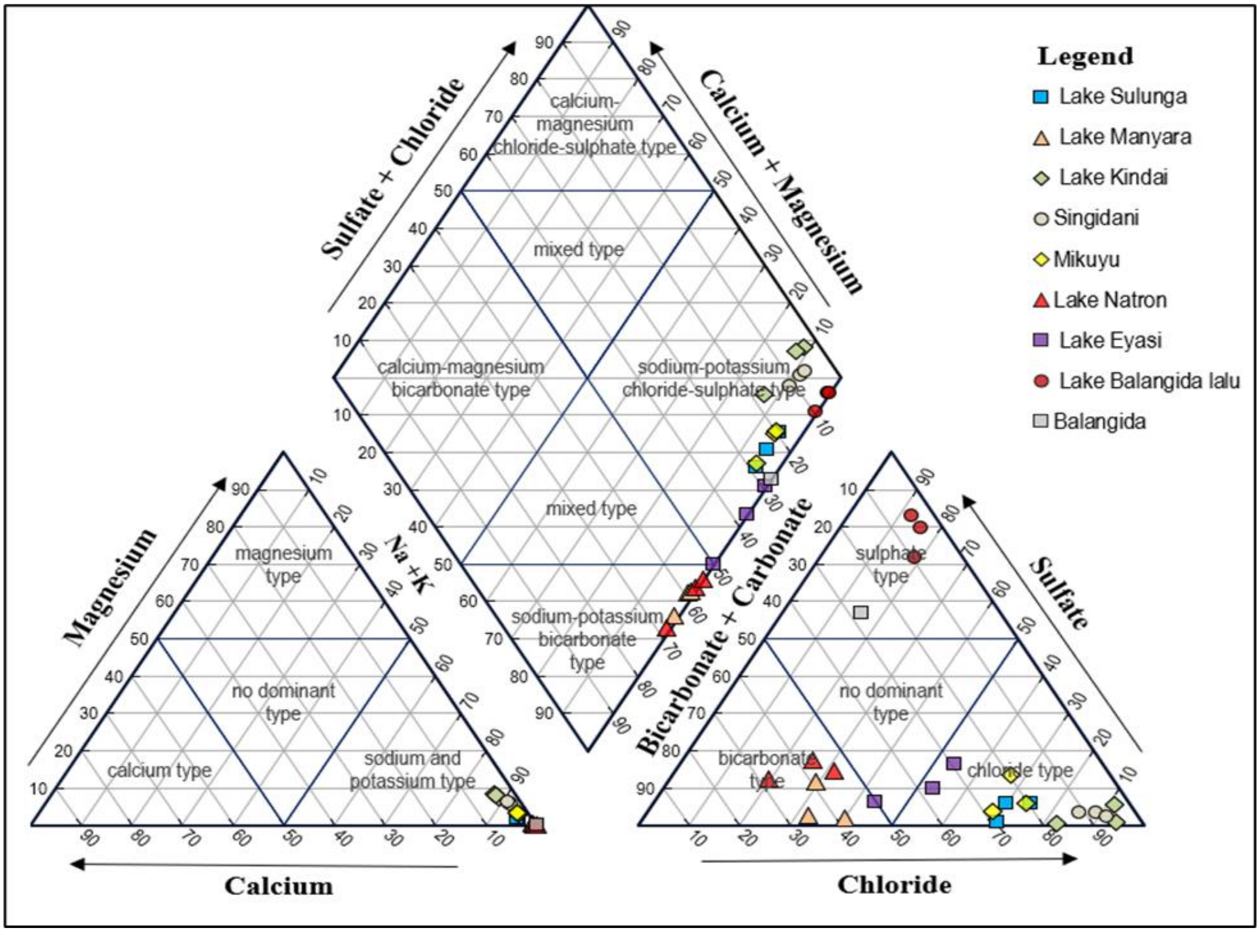


Figure 5: The Piper diagram showing the evolutional hydrochemical types of ETRV lakes

3.3 Geographical distributions of the IASW in ETRV

Figure 6 depicts the spatial geographical distribution of IASW in ETRV. The study revealed a decline in soda-saline characteristics from northern to central Tanzania. Soda and soda-saline lakes are predominantly in Arusha and Manyara regions. Saline-type lakes are predominantly found in the central regions of Singida and Dodoma. This distribution pattern is likely to be influenced by variations in geology, topography, and volcanic activity Figure 7. In northern Tanzania, the prevalence of volcanic rocks (Dawson, 2008; Ghiglieri et al., 2012; Kisaka et al., 2021; Lyu et al., 2018; Mizota et al., 1988; Nanyaro et al., 1984; Scoon, 2018) supports the formation of soda-saline lakes. In contrast, the central regions feature basement and consolidated sedimentary rocks

(Eriksson & Sandgren, 1999; Macdonald et al., 2000), leading to the development of non-soda lakes. The volcanic activity contributes to alkali-rich ions, supporting the formation of soda lakes, whereas the absence of such activity in central areas allows other lake types to form. Additionally, groundwater flow in basinal-flow systems can alter anion compositions transforming HCO_3^- to SO_4^{2-} and then to Cl^- (Tóth, 1999) which may play a role in the distribution of soda-saline lakes.

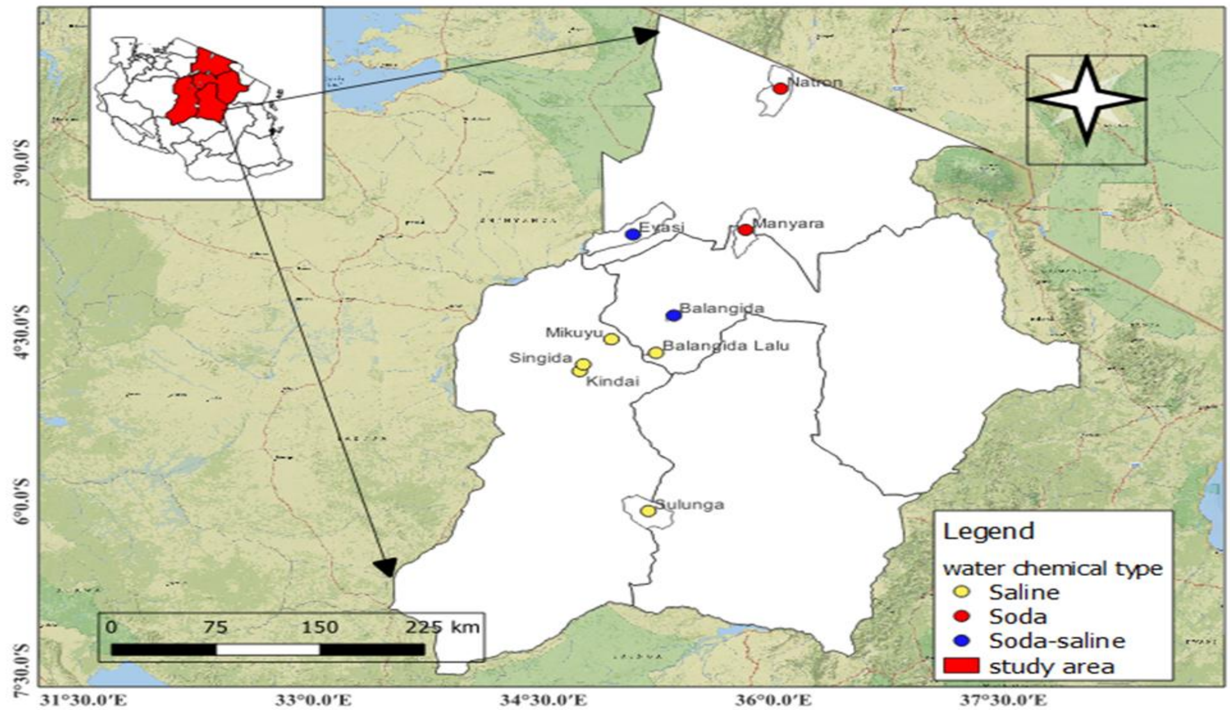


Figure 6: The geographical distributions of IASW in ETRV

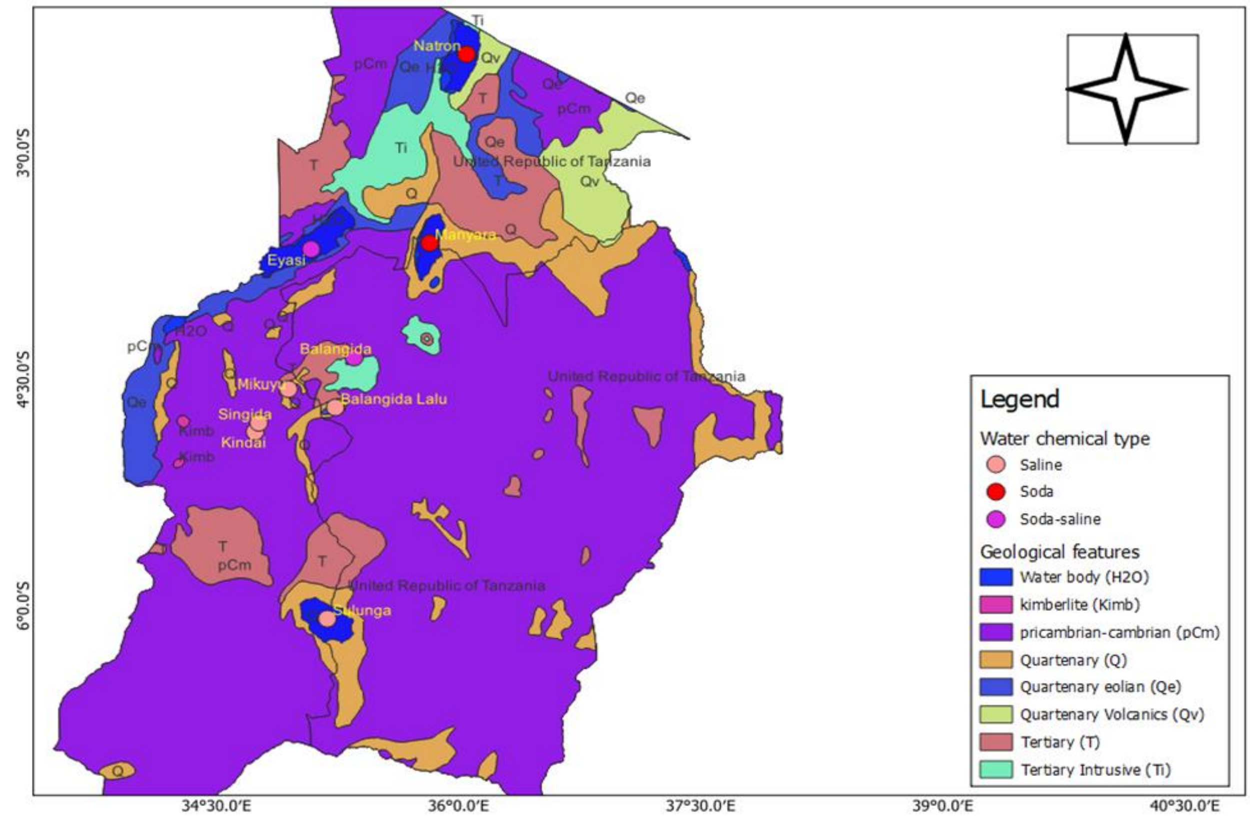


Figure 7: The geological features surrounding the IASW in the ETRV

3.4 Drought Analysis with satellite-based climate data in northern Tanzania

Figure 8 shows validation results comparing CHIRPS precipitation data and MERRA-2 temperature data to station data. The analysis yielded an RMSE of 0.94 ($R^2 = 0.54$) for MERRA-2 temperature data and 65.52 ($R^2 = 0.53$) for CHIRPS precipitation data. These results indicate that MERRA-2 and CHIRPS datasets are reliable and appropriate for use in drought studies, as they closely align with station-recorded measurements.

Figure 9 illustrates the SPEI trends over 3-, 6-, and 12-month intervals, using the satellite-based rainfall and temperature data across Lake Natron, Lake Manyara, and Lake Eyasi basins from 1981 to 2022. The 3-month SPEI captures frequent dry and wet events, while the 6- and 12-month scales better highlight significant, long-term drought patterns. The analysis revealed increasing drought severity across all basins, with severe drought events recorded from 1987 to 1992, 2000-2010, and 2012-2017. An extended drought from 2012 to 2017 further emphasizes this trend, which aligns with findings of rising drought frequency and intensity across East Africa (Gebremeskel et al., 2019; Polong et al., 2019). Previous investigations in the region have confirmed that the frequency of drought episodes has increased since 2000 (Slegers, 2008; Kijazi and Reason, 2009; Leweri *et al.*, 2021; Mdemu, 2021; Verhoeve *et al.*, 2021). The intensifying drought conditions, likely driven by climate-related shifts in precipitation and temperature, pose threats to the ecosystems of soda-saline lakes. These results highlight the need for proactive resource management and policy measures to safeguard lake health and secure water resources for future generations.

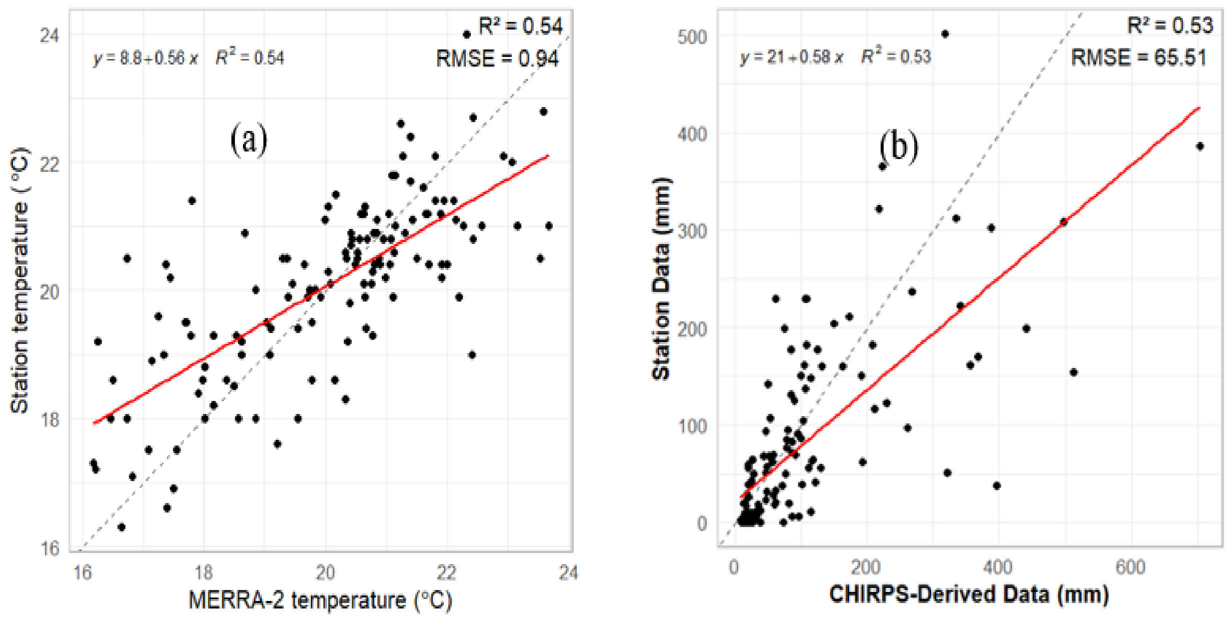
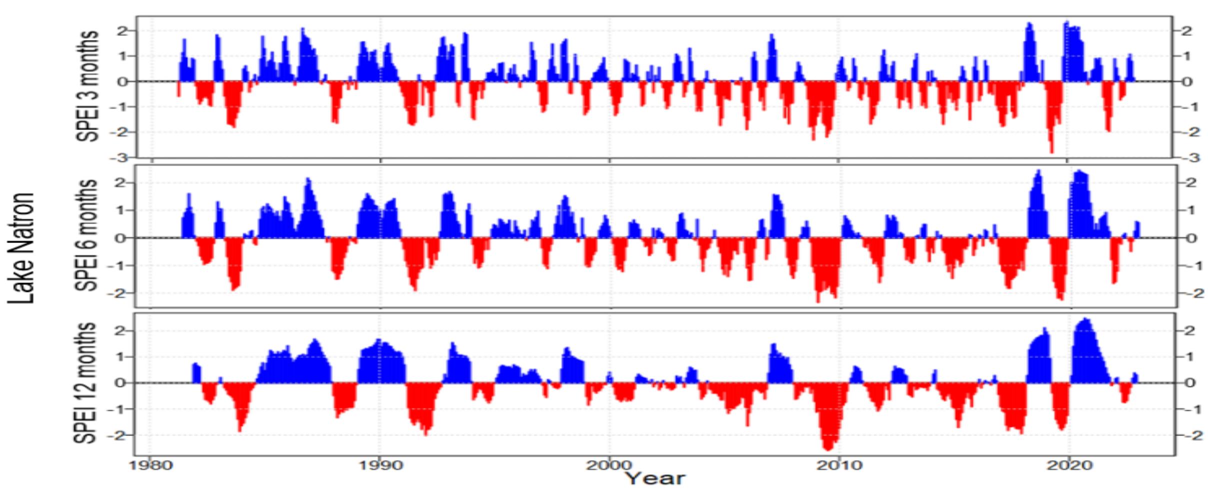


Figure 8: (a) Station temperature versus MERRA-2 temperature data (b) observed precipitation versus CHIRPS data



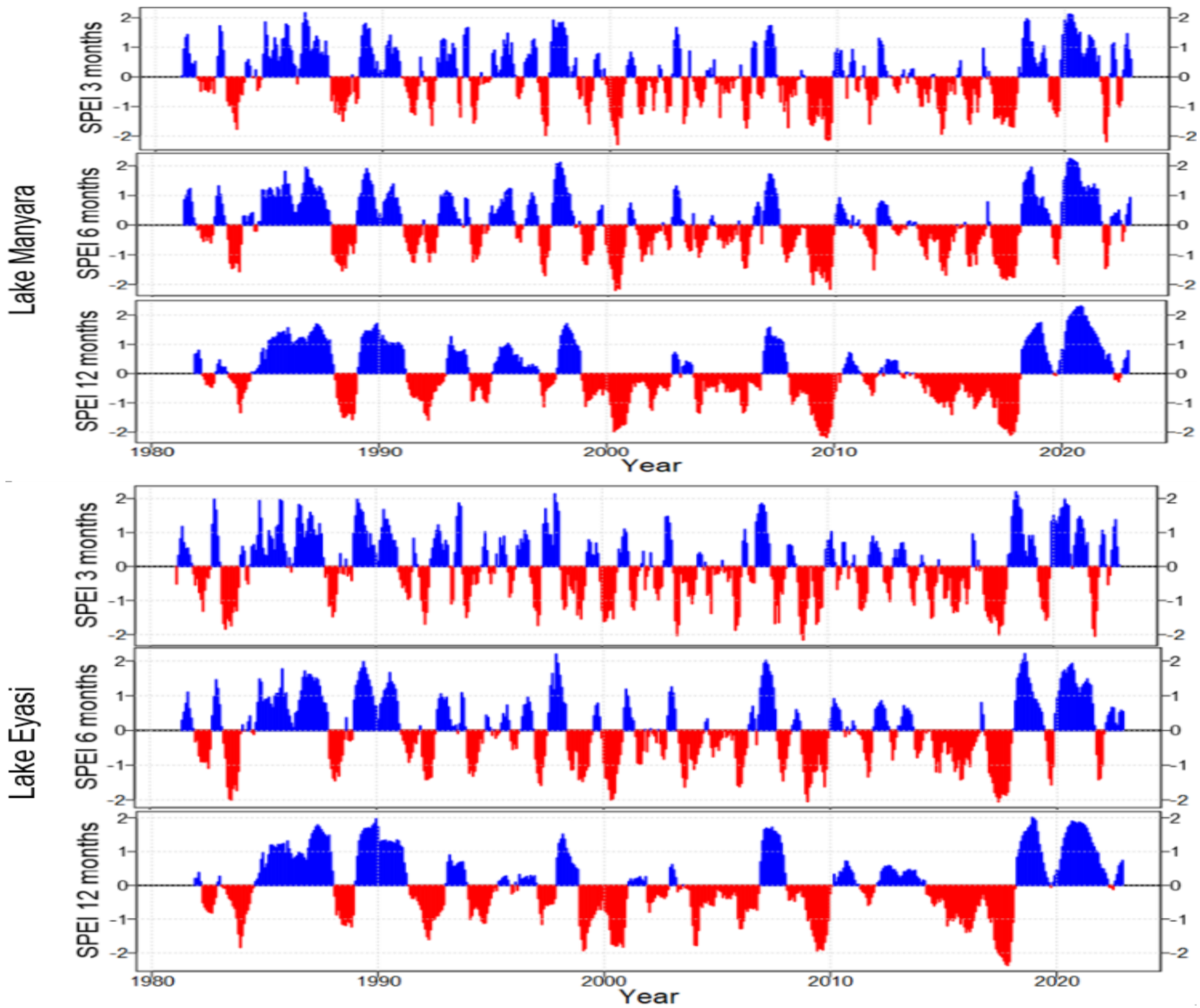


Figure 9: The SPEI evolution at 3-, 6-, and 12-month timescales for Lake Manyara, Lake Natron, and Lake Eyasi basins highlights the variation in the duration, severity, and intensity of dry and wet events.

3.6 Land Use and Land Cover (LULC) Changes in the northern Tanzania

3.6.1 Accuracy statement

The overall accuracies were above 80% while the Kappa coefficients were greater than 0.70 (Table 3). These results were within the acceptable range; therefore, we proceeded to use the classification outputs (Landis & Koch, 1977).

Table 3: Table 4 Accuracy Assessment

	2000	**2014**	**2023**
Overall accuracy	92.55	84.59	81.57
Kappa hat	0.87	0.75	0.72

3.6.2 LULC and Lake areas statistics and maps

Table 4 and Figure 10 show spatial and temporal changes in LULC classes. In 2000 and 2014, bareland dominated the study area (58.73% and 50.77%), followed by shrubs and grasses (21.80% and 33.47%). By 2023, shrubs and grasses became the largest LULC category (37.66%), with bareland close behind (37.48%). Built-up areas consistently covered the smallest area, while water bodies remained the second smallest, occupying 5.07%, 2.87%, and 3.05% each year.
The analysis of individual lakes showed that Lake Eyasi consistently had the largest area across all three study years (Table *5*). In contrast, Lake Manyara had the smallest area in 2000 (54,873.81 ha) and 2014 (21,760.61 ha). By 2023, however, Lake Natron had the smallest area (20,368.59 ha) indicating distinct patterns of area change among the lakes over time. In 2014, both lakes revealed declines in catchment areas (Figure 11), likely due to prolonged droughts from 2000 to 2017 (Figure 9), which reduced precipitation and water inflow, contributing to the observed lake shrinkage.

Table 4: LULC areas and percentages for 2000, 2014 and 2023

LULC Class	**2000**		**2014**		**2023**	
	Area (ha)	**Area (%)**	**Area (ha)**	**Area (%)**	**Area (ha)**	**Area (%)**
Water bodies	262304.42	5.07	148491.07	2.87	157900.61	3.05
Forest	334007.72	6.46	183211.33	3.54	258615.37	5
Shrubs & grasses	1127623.3	21.8	1731349.05	33.47	1948192.3	37.66
Bareland	3037905.51	58.73	2626045.29	50.77	1938675.6	37.48
Agricultural land	410050.59	7.93	479914.71	9.28	865253.47	16.73
Built up	748.8	0.01	3628.89	0.07	4003.99	0.08
Total	**5172640.34**	**100**	**5172640.34**	**100**	**5172641.34**	**100**

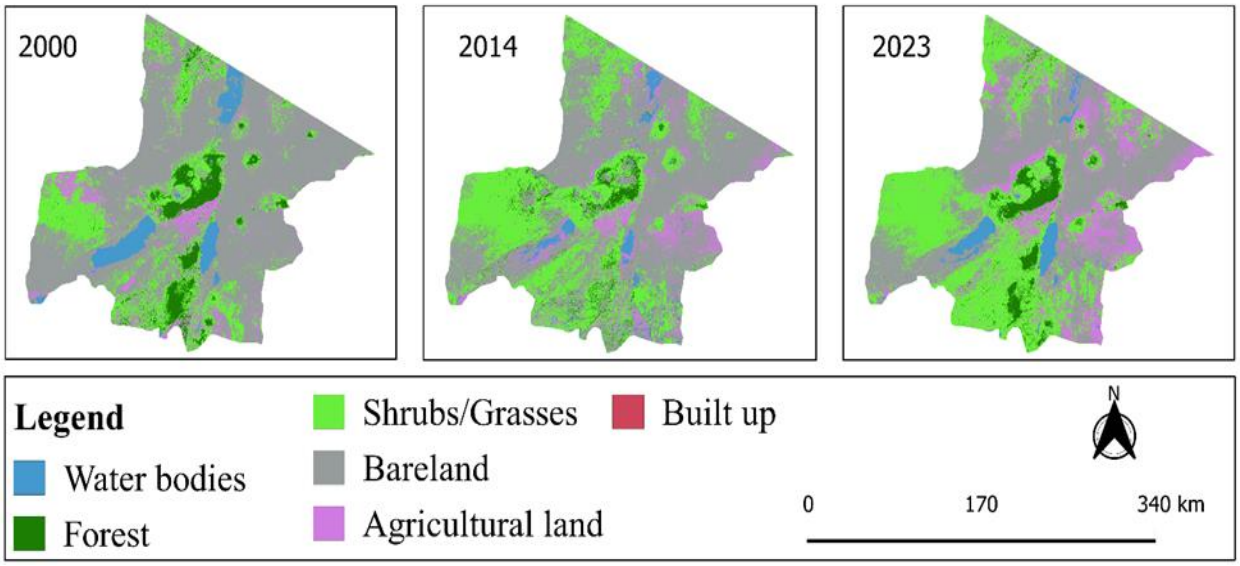


Figure 10: Map showing the spatial distribution of the various LULC classes over the study period

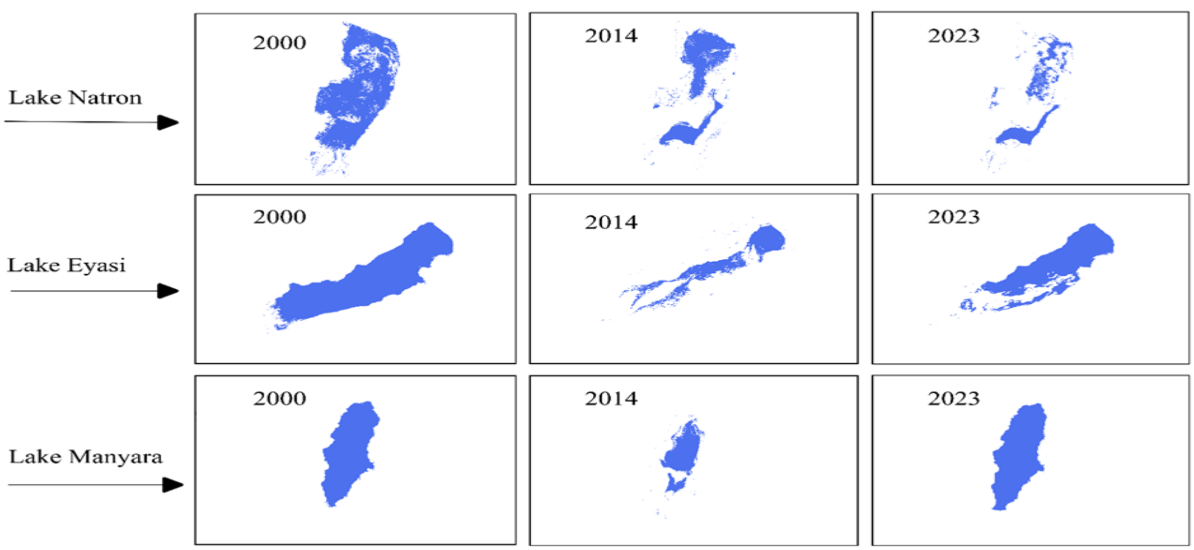


Figure 11: Maps showing the spatio-temporal dynamics of the three lakes in the study area

Table 5: Individual Lakes statistics for 2000, 2014 and 2023 in the study area

Lake	2000	2014	2023
	Area (ha)	Area (ha)	Area (ha)
Lake Natron	73332.90	34970.02	20368.59
Lake Eyasi	115284.80	35788.93	68479.04
Lake Manyara	54873.81	21760.61	55036.17

3.6.3 LULC and lake changes

Table 6 illustrates changes in various LULC classes over time. Between 2000 and 2014, forest areas declined by -45.15%, water bodies by -43.39% and bareland by -13.56%, while agricultural land expanded by 17.04%, built-up areas by 384.63%, and shrubs and grasses by 53.54%. From 2014 to 2023, all LULC categories except bareland showed area increases. Overall, between 2000 and 2023, water bodies (-39.80%), forests (-22.57%), and bareland (-36.18%) declined, while agricultural land (111.01%), built-up areas (434.72%), and shrubs and grasses (72.77%) increased. Similar trends of expanding in agricultural land and urban/built-up areas alongside shrinking water bodies have been observed in studies of the Urmia Lake basin in Iran and Lake Naivasha in Kenya, mainly due to human activities and climate impacts (Onywere, 2012; Chaudhari *et al.*, 2018). The expansion of built-up areas in the area is closely linked to population growth (Ministry of Finance and Planning, 2022), which drives agricultural expansion and intensification to meet food and commercial demands (Onyango et al., 2015). Increased agriculture typically leads to more water use for irrigation and applications of fertilizers, pesticides, and herbicides, which can alter water chemistry and promote algal blooms (Evans et al., 2019; Zahoor & Mushtaq, 2023). Previous studies highlight human activities as the primary cause of significant shifts in land use and water resources (Chaudhari et al., 2018). Over the past two decades, the study area has also experienced considerable deforestation, likely from anthropogenic activities. Deforestation accelerates soil erosion and nutrient run-off into lakes, altering their chemical compositions (Hay, 1998).

Table 6: LULC changes between the study years

LULC class	2000-2014		2014-2023		2000-2023	
	ha	**%**	**ha**	**%**	**ha**	**%**
Water bodies	-113813.35	-43.39	9409.54	6.34	-104403.81	-39.8
Forest	-150796.39	-45.15	75404.04	41.16	-75392.35	-22.57
Shrubs & grasses	603725.75	53.54	216843.25	12.52	820569	72.77
Bareland	-411860.22	-13.56	-687369.69	-26.18	-1099229.91	-36.18
Agricultural land	69864.12	17.04	385338.76	80.29	455202.88	111.01
Built up	2880.09	384.63	375.1	10.34	3255.19	434.72

Table 7: Changes in individual Lake area coverage between the study years

Lake name	2000-2014	2014-2023	2014-2023
	Area (ha)	Area (ha)	Area (ha)
Lake Natron	-38,362.88	-14,601.43	-52,964.31
Lake Eyasi	-79,495.87	32,690.11	-46,805.76
Lake Manyara	-33,113.20	33,275.56	162.36

Further analysis of individual lakes revealed notable changes in area coverage over the study periods (Table 7). Lake Natron experienced a steady decrease from 2000 to 2023, while Lakes Eyasi and Manyara showed reductions from 2000–2014 followed by expansions from 2014–2023 (Table 7). Overall, Lake Natron and Lake Eyasi recorded net area losses of -52,964.31 ha and -46,805.76 ha, respectively, whereas Lake Manyara had a slight net gain of 162.36 ha (Table 7). The decline in the lake catchment area is linked to water abstraction (Goshime et al., 2019) and climate variability (Yao et al., 2023), affecting water volumes and, consequently, lake chemistry and ecosystem health. Our findings align with prior studies on Lake Natron's surface area, which showed variability due to climate fluctuations and watershed degradation (Tebbs et al., 2013). Similarly, stakeholder analyses identified water depletion, local human activities, siltation, and evaporation as primary challenges for Lake Manyara (Janssens de Bisthoven et al., 2020). Research on Eastern Rift Valley Lakes, including Natron, Eyasi, and Manyara, also associates water level shifts with geological, climatic, and biological factors (Yanda & Madulu, 2005).

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This thesis presents a detailed analysis of the chemistry of the inland soda-saline lake waters in the East African Rift Valley (EARV) system, focusing on the ETRV. We compiled and reported chemical data from 56 inland soda salt waters in the EARV into a comprehensive database. The results of our study revealed that the dominance sequence of major cations and anions in the EARV is as follows: $Na^{+} > K^{+} > Ca^{2+} > Mg^{2+}$ and $HCO_3^{-} + CO_3^{2-} > Cl^{-} > SO_4^{2-}$. Among the examined lakes, 73.2% were soda water chemical types, 12.5% were soda-saline water, and 14.3% were saline water chemical types. The spatial distributions of Na^{+}, Cl^{-}, CO_3^{2-}, and TDS in the EARV revealed a gradual increase in the concentration gradient of Na^{+}, Cl^{-}, CO_3^{2-}, and TDS (salinity) from the northern to the southern regions of the eastern branch of the EARV. However, Lake Afrera, situated in the Danakil depression in the north of Ethiopia and Ugandan lakes (Western Rift), stands out as a significant exception from this pattern.

In the ETRV lakes, Na^{+} dominates, with lower amounts of K^{+}, Ca^{2+}, and Mg^{2+}, and mixed dominance of HCO_3^{-} + CO_3^{2-}, Cl^{-}, and SO_4^{2-}. From North to Central Tanzania, we observed decreasing soda lake characteristics. Soda-type and soda-saline lakes were more widespread in northern Tanzania (Arusha and Manyara), whereas saline lakes were common in the middle region between Dodoma and Singida. The volcanic predominant in northern Tanzania likely influenced the dominance of soda and soda-saline lakes in northern Tanzania (Arusha and Manyara). The regional groundwater gravity flow could also account for the observed trend of soda-saline characteristics in the ETRV. We observed temperature and precipitation variability in northern Tanzania. The SPEI results showed drought episodes from 1987, with prolonged droughts between 2000 and 2017 perhaps caused by regional and global climate change. The intricate relationship between the climate, soils, and geological features in northern Tanzania plays a crucial role in triggering the creation of soda-saline lakes. For the 23-year study period (2000–2023), we noted LULC changes. Water bodies decreased by 39.80%, forests by 22.57%, and bare land by 36.18%. Water bodies fell 39.80%, woods 22.57%, and barren ground 36.18%. Conversely, agricultural land rose 111.01%, built-up areas 434.72%, and bushes and grasses 72.77%. The analysis of the individual lakes revealed decreased area coverage in 2014 for all lakes while in 2023 lake area coverage of Natron decreased while for Lake Eyasi and Manyara, the coverage area increased. Human actions such as an increase in agricultural and built-up areas reflect population increases and suggest the LULC alterations. The decrease in waterbodies and forests negatively harms lake ecosystems and biodiversity. Policymakers and stakeholders must consider LULC trends for sustainable development and conservation. Understanding the complex interactions between climate change, drought, and the ecosystem in this region requires more investigation.

4.2 Recommendations

According to the findings of this study, the following recommendations can be made:

1. Establish a Regular Monitoring System: It is important to establish and implement a continuous monitoring system to track changes in the chemistry of soda-saline lakes over time. Ongoing monitoring will provide valuable insights into any shifts in lake chemistry and offer early warnings of potential changes due to climatic or anthropogenic influences.
2. Implement Climate Change Mitigation Strategies: Climate change initiatives aiming at reducing the frequency and severity of droughts should be prioritized. This includes optimizing water management practices, reforestation and anti-deforestation programmes, controlling the emission of pollutants from industry and promoting sustainable land use practices.
3. Incorporate Land Use and Land Cover (LULC) Change into Regional Planning: It is important to integrate patterns of land use and land cover change into regional planning frameworks. This should include policies that address deforestation and promote sustainable land use practices, as the reduction in water bodies and forests, coupled with the expansion of agricultural and urban areas, highlights the urgent need for sustainable land management to preserve biodiversity and ecosystem services.
4. Raise Public Awareness on the Ecological Importance of Soda Lakes: Raising public awareness about the ecological value of soda lakes is vital for fostering community support for conservation efforts. Initiatives of educating the public on the importance of these ecosystems will encourage sustainable practices that help reduce environmental degradation

5. KEY SCIENTIFIC FINDINGS AND IMPORTANT OUTPUT

1. I have compiled and reported chemical data and classified EARV inland soda salt waters into a comprehensive database based on their distinctive water chemical type. I have determined that 73.2% of the lakes were soda type, 12.5% soda-saline type and 14.3% saline type.
2. This study revealed a north-to-south gradual increase in the concentration gradient of Na^+, Cl^-, $HCO_3^- + CO_3^{2-}$ in relation to the volcanic spatial pattern, and TDS (salinity) across the eastern branch of the EARV.
3. Soda and soda-saline lakes were predominant in northern Tanzania (Arusha and Manyara), while saline lakes were more common in the central region (Singida and Dodoma).
4. In northern Tanzania, prolonged drought episodes were observed between 2000 and 2017.
5. LULC analysis showed declines in water bodies, forests, and bare land, with increases in agricultural land, built-up areas, and bush/grassland
6. Between 2000 to 2014, all lake catchment areas decreased, but between 2014 and 2023, only Lake Natron continued to shrink, while Lakes Eyasi and Manyara expanded.

References

Abdallah, E. A., Kasanzu, C. H., Kinabo, C. P., & Imai, A. (2023). Hydro-geochemistry and Related Processes Controlling the Composition of Thermal Waters in the Lake Natron Basin, Northern Tanzania. *Tanzania Journal of Science*, *49*(3), 677–689. https://doi.org/10.4314/tjs.v49i3.11

Ahmed, A., Rotich, B., & Czimber, K. (2024). Assessment of the environmental impacts of conflict-driven Internally Displaced Persons: A sentinel-2 satellite based analysis of land use/ cover changes in the Kas locality, Darfur, Sudan. *PLoS ONE*, *19*(5 May), 1–19. https://doi.org/10.1371/journal.pone.0304034

Ali, Y., Simachew, A., & Gessesse, A. (2022). Diversity of Culturable Alkaliphilic Nitrogen-Fixing Bacteria from a Soda Lake in the East African Rift Valley. *Microorganisms*, *10*(9). https://doi.org/10.3390/microorganisms10091760

Boros, E. (2023). Estimation method for carbonate in natural alkaline soda lake-waters. *MethodsX*, *10*(January), 102175. https://doi.org/10.1016/j.mex.2023.102175

Boros, E., & Kolpakova, M. (2018). A review of the defining chemical properties of soda lakes and pans: An assessment on a large geographic scale of Eurasian inland saline surface waters. *PLoS ONE*, *13*(8), 1–20. https://doi.org/10.1371/journal.pone.0202205

Catherine, A. M., Revocatus, M., & Hussein, S. (2015). Will Ngorongoro Conservation Area remain a world heritage site amidst increasing human footprint? *International Journal of Biodiversity and Conservation*, *7*(9), 394–407. https://doi.org/10.5897/ijbc2015.0837

Chaudhari, S., Felfelani, F., Shin, S., & Pokhrel, Y. (2018). Climate and anthropogenic contributions to the desiccation of the second largest saline lake in the twentieth century. *Journal of Hydrology*, *560*, 342–353. https://doi.org/10.1016/j.jhydrol.2018.03.034

Dawson, J. B. (2008a). *The Gregory rift valley and Neogene-recent volcanoes of northern Tanzania. Geological Society of London.*

Dawson, J. B. (2008b). The Gregory rift valley and Neogene-recent volcanoes of northern Tanzania. *Geological Society of London.*, *33*, 33–38.

Deocampo, D. M., & Renaut, R. W. (2016). Geochemistry of African soda lakes. *Soda Lakes of East Africa*, 77–93. https://doi.org/10.1007/978-3-319-28622-8

Deocampo, Daniel M. (2004). Hydrogeochemistry in the Ngorongoro Crater, Tanzania, and implications for land use in a World Heritage Site. *Applied Geochemistry*, *19*(5), 755–767. https://doi.org/10.1016/j.apgeochem.2003.10.006

Eriksson, M. G., & Sandgren, P. (1999). Mineral magnetic analyses of sediment cores recording recent soil erosion history in central Tanzania. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *152*(3–4), 365–383. https://doi.org/10.1016/S0031-0182(99)00043-7

Eugster, H. P., & Jones, B. F. (1979). Behavior of major solutes during closed basin- lakes brine evolution. In *American Journal of Science* (Vol. 279, Issue 6, pp. 609–631). https://doi.org/10.2475/ajs.279.6.609

Eugster, Hans P. (1970). Chemistry and origin of the brines of Lake Magadi, Kenya. *Mineral. Soc. Amer. Spec. Pap.*, *3,* 213–235.

Eugster, Hans P. (1980). Geochemistry of Evaporitic Lacustrine Deposits. *Annual Review of Earth Platenary Science*, *8*(1), 35–63. https://doi.org/10.1016/0012-8252(84)90008-4

Evans, A. E., Mateo-Sagasta, J., Qadir, M., Boelee, E., & Ippolito, A. (2019). Agricultural water pollution: key knowledge gaps and research needs. *Current Opinion in Environmental Sustainability*, *36*, 20–27. https://doi.org/10.1016/j.cosust.2018.10.003

Fazi, S., Butturini, A., Tassi, F., Amalfitano, S., Venturi, S., Vazquez, E., Clokie, M., Wanjala, S.

W., Pacini, N., & Harper, D. M. (2018). Biogeochemistry and biodiversity in a network of saline–alkaline lakes: Implications of ecohydrological connectivity in the Kenyan Rift Valley. *Ecohydrology and Hydrobiology*, *18*(2), 96–106. https://doi.org/10.1016/j.ecohyd.2017.09.003

Foster, A., Ebinger, C., Mbede, E., & Rex, D. (1997). Tectonic development of the northern Tanzania sector of the East African Rift System Tectonic development of the northern Tanzanian sector of the East African Rift. *Journal of the Geological Society*, *154*(4), 689–700. https://doi.org/10.1144/gsjgs.154.4.0689

Fritz, B., Zins-Pawlas, M.-P., & Gueddari, M. (1987). Geochemistry of silica-rich brines from Lake Natron (Tanzania). Géochimie des saumures riches en silice du lac Natron (Tanzanie). *Sciences Géologiques. Bulletin*, *40*(1), 97–110. https://doi.org/10.3406/sgeol.1987.1753

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Scientific Data*, *2*, 1–21. https://doi.org/10.1038/sdata.2015.66

Gebremeskel, G., Tang, Q., Sun, S., Huang, Z., Zhang, X., & Liu, X. (2019). Droughts in East Africa: Causes, impacts and resilience. *Earth-Science Reviews*, *193*(June 2018), 146–161. https://doi.org/10.1016/j.earscirev.2019.04.015

Ghiglieri, G., Pittalis, D., Cerri, G., & Oggiano, G. (2012). Hydrogeology and hydrogeochemistry of an alkaline volcanic area: The NE Mt. Meru slope (East African Rift-Northern Tanzania). *Hydrology and Earth System Sciences*, *16*(2), 529–541. https://doi.org/10.5194/hess-16-529-2012

Godebo, T. R., Jeuland, M. A., Paul, C. J., Belachew, D. L., & McCornick, P. G. (2021). Water quality threats, perceptions of climate change and behavioral responses among farmers in the ethiopian rift valley. *Climate*, *9*(6). https://doi.org/10.3390/cli9060092

Goshime, D. W., Absi, R., Ledésert, B., Dufour, F., & Haile, A. T. (2019). Impact of water abstraction on the water level of Lake Ziway, Ethiopia. *WIT Transactions on Ecology and the Environment*, *239*, 67–78. https://doi.org/10.2495/WS190071

Grant, W.D., & Jones, B. E. (2016). Bacteria, Archaea and Viruses of Soda Lakes. In M. Schagerl (Ed.), *Soda Lake of East Africa* (pp. 97–148). Springer International Publishing Switzerland. https://doi.org/10.1007/978-3-319-28622-8_5

Grant, William D. (2004). Introductory Chapter: Half a Lifetime in Soda Lakes. In A.Ventosa (Ed.), *Halophilic Microorganisms* (pp. 17–31). Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-662-07656-9_1

Grant, William D, & Yu, D. (2011). Distribution and Diversity of Soda Lake Alkaliphiles. In H. K. (Ed.), *Extrimophiles Handbook* (pp. 27–54). Springer, Tokyo. https://doi.org/10.1007/978-4-431-53898-1

Hay, W. W. (1998). Detrital sediment fluxes from continents to oceans. *Chemical Geology*, *145*(3–4), 287–323. https://doi.org/10.1016/S0009-2541(97)00149-6

Hecky, R. E., & Kilham, P. (1973). Diatoms in Alkaline, Saline Lakes: Ecology and Geochemical Implications. *Limnology and Oceanography*, *18*(1), 53–71. https://doi.org/10.4319/lo.1973.18.1.0053

Inelova, Z., Zaparina, Y., Mile, O., & Boros, E. (2024). Large-scale assessment of characteristic plant species on Eurasian saline and alkaline soda ecosystems. *Ecological Indicators*, *166*(March), 112431. https://doi.org/10.1016/j.ecolind.2024.112431

Janssens de Bisthoven, L., Vanhove, M. P. M., Rochette, A. J., Hugé, J., Verbesselt, S., Machunda, R., Munishi, L., Wynants, M., Steensels, A., Malan-Meerkotter, M., Henok, S., Nhiwatiwa, T., Casier, B., Kiwango, Y. A., Kaitila, R., Komakech, H., & Brendonck, L. (2020). Social-ecological assessment of Lake Manyara basin, Tanzania: A mixed method approach. *Journal of Environmental Management*, *267*(September 2019). https://doi.org/10.1016/j.jenvman.2020.110594

Jeilu, O., Gessesse, A., Simachew, A., Johansson, E., & Alexandersson, E. (2022). Prokaryotic and eukaryotic microbial diversity from three soda lakes in the East African Rift Valley determined by amplicon sequencing. *Frontiers in Microbiology*, *13*(December), 1–14. https://doi.org/10.3389/fmicb.2022.999876

Jones, B. E., Grant, W. D., Duckworth, A. W., & Owenson, G. G. (1998). Microbial diversity of soda lakes. *Extremophiles*, *2*(3), 191–200. https://doi.org/10.1007/s007920050060

Jones, B. F., & Deocampo, D. M. (2003). Geochemistry of saline lakes. *Treatise on Geochemistry*, *5–9*(Figure 1), 393–424. https://doi.org/10.1016/B0-08-043751-6/05083-0

Jozsef Toth. (1999). Groundwater as a geologic agent : An overview of the causes , processes , and manifestations. *Hydrogeology Journal*, *7*(January), 1–14.

Kaushal, S. S., Likens, G. E., Pace, M. L., Reimer, J. E., Maas, C. M., Galella, J. G., Utz, R. M., Duan, S., Kryger, J. R., Yaculak, A. M., Boger, W. L., Bailey, N. W., Haq, S., Wood, K. L., Wessel, B. M., Park, C. E., Collison, D. C., Aisin, B. Y. 'aaqo. I., Gedeon, T. M., … Woglo, S. A. (2021). Freshwater salinization syndrome: from emerging global problem to managing risks. In *Biogeochemistry* (Vol. 154, Issue 2). Springer International Publishing. https://doi.org/10.1007/s10533-021-00784-w

Kempe, S., & Kazmierczak, J. (2002). Biogenesis and early life on earth and Europa: Favored by an alkaline ocean? *Astrobiology*, *2*(1), 123–130. https://doi.org/10.1089/153110702753621394

Kijazi, A. L., & Reason, C. J. C. (2009). Analysis of the 1998 to 2005 drought over the northeastern highlands of Tanzania. *Climate Research*, *38*(3), 209–223. https://doi.org/10.3354/cr00784

Kisaka, M., Fontijn, K., Shemsanga, C., Tomašek, I., Gaduputi, S., Debaille, V., Delcamp, A., & Kervyn, M. (2021). The late Quaternary eruptive history of Meru volcano, northern Tanzania. *Journal of Volcanology and Geothermal Research*, *417*. https://doi.org/10.1016/j.jvolgeores.2021.107314

Lameck, S. A., Skutai, J., & Boros, E. (2023). Review of chemical properties of inland soda and saline waters in East Africa (rift valley region). *Journal of Hydrology: Regional Studies*, *46*(January), 101323. https://doi.org/10.1016/j.ejrh.2023.101323

Landis, J. R., & Koch, G. G. (1977). The Measurement of Observer Agreement for Categorical Data Data for Categorical of Observer Agreement The Measurement. *Biometrics*, *33*(1), 159–174. https://doi.org/https://doi.org/10.2307/2529310

Leweri, C. M., Msuha, M. J., & Treydte, A. C. (2021). Rainfall variability and socio-economic constraints on livestock production in the Ngorongoro Conservation Area, Tanzania. *SN Applied Sciences*, *3*(1), 1–10. https://doi.org/10.1007/s42452-020-04111-0

Li, C., Wen, H., Liu, H., Xiong, W., Guo, P., Zhong, K., & Liang, H. (2024). Controls of water salinity on biological diversity and productivity in the Late Paleozoic alkaline lake, NW Junggar Basin, NW China. *Journal of Asian Earth Sciences*, *275*, 106288. https://doi.org/https://doi.org/10.1016/j.jseaes.2024.106288

Lyu, H., Watanabe, T., Kilasara, M., & Funakawa, S. (2018). Effects of climate on distribution of soil secondary minerals in volcanic regions of Tanzania. *Catena*, *166*(December 2017), 209–219. https://doi.org/10.1016/j.catena.2018.04.005

M. Onywere, S. (2012). Use of Remote Sensing Data in Evaluating the Extent of Anthropogenic Activities and their Impact on Lake Naivasha, Kenya. *The Open Environmental Engineering Journal*, *5*(1), 9–18. https://doi.org/10.2174/1874829501205010009

Macdonald, A. M., Davies, J., Nations, U., Programme, E., Olorunfemi, F., Rilwanu, T. Y., Inkani, A. I., Olasehinde, P. I., Journal, K., abdul, Solomon, S., Nwankwoala, H. O., Danert, K., Gesti Canuto, J., British Geological Survey, Nanbakhsh, H., Tasi ', O, I. E., Mallam I, … Decision, M. (2000). A brief review of groundwater for rural water supply in sub-Saharan Africa. *Journal of Environment and Earth Science*, *1*(May), 1–17. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:REMOTE+SENSING+APPLICATIONS+to+GROUNDWATER#5%0Ahttp://garj.org/garjas/home%0Ahttps://www.unicef.org/wash/files/Guidance_Note_005.pdf%0Ahttp://www.rural-water-supply.net/en/resources/details/130

Mdemu, M. V. (2021). Community's Vulnerability to Drought-Driven Water Scarcity and Food Insecurity in Central and Northern Semi-arid Areas of Tanzania. *Frontiers in Climate*, *3*(October), 1–14. https://doi.org/10.3389/fclim.2021.737655

Mgimwa, E. F., John, J. R., & Lugomela, C. V. (2021). The influence of physical – - chemical variables on phytoplankton and lesser flamingo (Phoeniconaias minor) abundances in Lake. *African Journal of Ecology*, *59*(3), 667–675. https://doi.org/10.1111/aje.12863

Ministry of Finance and Planning, N. B. of S. T. (2022). *Age and Sex Distribution Report*. 1–23.

Mizota, C., Kawasaki, I., & Wakatsuki, T. (1988). Clay mineralogy and chemistry of seven pedons formed in volcanic ash, Tanzania. *Geoderma*, *43*(2–3), 131–141. https://doi.org/10.1016/0016-7061(88)90039-0

Musie, W., & Gonfa, G. (2023). Fresh water resource, scarcity, water salinity challenges and possible remedies: A review. *Heliyon*, *9*(8), e18685. https://doi.org/10.1016/j.heliyon.2023.e18685

Mwabumba, M., Yadav, B. K., Rwiza, M. J., Larbi, I., Dotse, S. Q., Limantol, A. M., Sarpong, S., & Kwawuvi, D. (2022). Rainfall and temperature changes under different climate scenarios at the watersheds surrounding the Ngorongoro Conservation Area in Tanzania. *Environmental Challenges*, *7*(August 2021), 100446. https://doi.org/10.1016/j.envc.2022.100446

Nanyaro, J. T., Aswathanarayana, U., Mungure, J. S., & Lahermo, P. W. (1984). A geochemical model for the abnormal fluoride concentrations in waters in parts of northern Tanzania. *Journal of African Earth Sciences*, *2*(2), 129–140. https://doi.org/10.1016/s0731-7247(84)80007-5

Olaka, L. A., Odada, E. O., Trauth, M. H., & Olago, D. O. (2010). The sensitivity of East African rift lakes to climate fluctuations. *Journal of Paleolimnology*, *44*(2), 629–644. https://doi.org/10.1007/s10933-010-9442-4

Onyango, J., Irvine, K., Bruggen, J. J. A. Van, Kitaka, N., & Kreuzinger, N. (2015). Agricultural Expansion and Water Pollution : The Yin-Yang in the Quality of Natural Water Resources. *African Centre for Technology Studies*, *9*(July), 1–29.

Owen, R. B., Renaut, R. W., & Lowenstein, T. K. (2018). Spatial and temporal geochemical variability in lacustrine sedimentation in the East African Rift System: Evidence from the Kenya Rift and regional analyses. *Sedimentology*, *65*(5), 1697–1730. https://doi.org/10.1111/sed.12443

Pecoraino, G., Alessandro, W. ., & Inguaggiato, S. (2015). The other side of the coin: geochemistry of alkaline lakes in volcanic areas. *Volcanic Lakes*, 219–237. https://doi.org/10.1007/978-3-

642-36833-2
Polong, F., Chen, H., Sun, S., & Ongoma, V. (2019). Temporal and spatial evolution of the standard precipitation evapotranspiration index (SPEI) in the Tana River Basin, Kenya. *Theoretical and Applied Climatology*, *138*(1–2), 777–792. https://doi.org/10.1007/s00704-019-02858-0
Robinson, J. V. (2015). *The Ecology of East African Soda Lakes : Implications for lesser flamingo (Phoeniconaias minor) feeding behaviour Thesis submitted for the degree of Doctor of Philosophy at the University of Leicester By*. *June*.
Rodriguez-Galiano, V. F., Ghimire, B., Rogan, J., Chica-Olmo, M., & Rigol-Sanchez, J. P. (2012). An assessment of the effectiveness of a random forest classifier for land-cover classification. *ISPRS Journal of Photogrammetry and Remote Sensing*, *67*(1), 93–104. https://doi.org/10.1016/j.isprsjprs.2011.11.002
Schagerl, Michael, & Renaut, R. W. (2016). Dipping into the Soda Lakes of East Africa. *Soda Lakes of East Africa*, *12*, 1–408. https://doi.org/10.1007/978-3-319-28622-8
Scoon, R. N. (2018). Geology of national parks of central/Southern Kenya and Northern Tanzania: Geotourism of the Gregory Rift Valley, active Volcanism and regional plateaus. In *Geology of National Parks of Central/Southern Kenya and Northern Tanzania: Geotourism of the Gregory Rift Valley, Active Volcanism and Regional Plateaus*. https://doi.org/10.1007/9783319737850
Scoon, R. N. (2020). Geotourism, Iconic Landforms and Island-Style Speciation Patterns in National Parks of East Africa. *Geoheritage*, *12*(3). https://doi.org/10.1007/s12371-020-00486-z
Sherrod, B. D. R., Magigita, M. M., & Kwelwa, S. (2013). Geologic Map of Oldonyo Lengai Volcano and Surroundings, Arusha Region, United Republic of Tanzania. *USGS Report*, 1–61.
Slegers, M. F. W. (2008). "If only it would rain": Farmers' perceptions of rainfall and drought in semi-arid central Tanzania. *Journal of Arid Environments*, *72*(11), 2106–2123. https://doi.org/10.1016/j.jaridenv.2008.06.011
Sorokin, D. Y., Banciu, H. L., & Muyzer, G. (2015). Functional microbiology of soda lakes. *Current Opinion in Microbiology*, *25*, 88–96. https://doi.org/10.1016/j.mib.2015.05.004
Sorokin, D. Y., Berben, T., Melton, E. D., Overmars, L., Vavourakis, C. D., & Muyzer, G. (2014). Microbial diversity and biogeochemical cycling in soda lakes. *Extremophiles*, *18*(5), 791–809. https://doi.org/10.1007/s00792-014-0670-9
Tebbs, E. J., Remedios, J. J., Avery, S. T., & Harper, D. M. (2013). Remote sensing the hydrological variability of Tanzania ' s Lake Natron , a vital Lesser Flamingo breeding site under threat. *Ecohydrology & Hydrobiology*, *13*(2), 148–158. https://doi.org/10.1016/j.ecohyd.2013.02.002
Thonfeld, F., Steinbach, S., Muro, J., & Kirimi, F. (2020). Long-term land use/land cover change assessment of the Kilombero catchment in Tanzania using random forest classification and robust change vector analysis. *Remote Sensing*, *12*(7). https://doi.org/10.3390/rs12071057
Verhoeve, S. L., Keijzer, T., Kaitila, R., Wickama, J., & Sterk, G. (2021). Northern Tanzania. *Remote Sensing*, *13*(22), 4592. https://doi.org/10.1007/978-94-011-7129-8_15
Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1
Vye-Brown, C., Crummy, J., Smith, K., Mruma, A., & Kabelwa, H. (2014). Volcanic hazards in

Tanzania. *British Geological Survey*.
Westberg, D. J., Stackhouse, P. W., Crawley, D. B., Hoell, J. M., Chandler, W. S., & Zhang, T. (2013). An analysis of NASA's merra meteorological data to supplement observational data for calculation of climatic design conditions. *ASHRAE Transactions*, *119*(PART 2), 210–221.
Yanda, P. Z., & Madulu, N. F. (2005). Water resource management and biodiversity conservation in the Eastern Rift Valley Lakes, Northern Tanzania. *Physics and Chemistry of the Earth*, *30*(11-16 SPEC. ISS.), 717–725. https://doi.org/10.1016/j.pce.2005.08.013
Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J. F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743–749. https://doi.org/10.1126/SCIENCE.ABO2812
Yona, C., Makange, M., Moshiro, E., Chengula, A., & Misinzo, G. (2022). Water pollution at Lake Natron Ramsar site in Tanzania : A threat to aquatic life. *Ecohydrology & Hydrobiology*, *xxxx*, 1–11. https://doi.org/10.1016/j.ecohyd.2022.11.001
Zahoor, I., & Mushtaq, A. (2023). Water Pollution from Agricultural Activities: A Critical Global Review. *International Journal of Chemical and Biochemical Sciences*, *23*(1), 164–176.
Zaitsev, A. N., & Keller, J. (2006). Mineralogical and chemical transformation of Oldoinyo Lengai natrocarbonatites, Tanzania. *Lithos*, *91*(1–4), 191–207. https://doi.org/10.1016/j.lithos.2006.03.018
Zebire, D. A., Ayele, T., & Ayana, M. (2019). Characterizing soils and the enduring nature of land uses around the Lake Chamo Basin in South-West Ethiopia. *Journal of Ecology and Environment*, *43*(1), 1–32. https://doi.org/10.1186/s41610-019-0104-9